

Acceleration Effects on Fluid-Sediment Interaction

Ole Secher Madsen

Ralph M. Parsons Laboratory, 48-216c

Department of Civil and Environmental Engineering

Massachusetts Institute of Technology

Cambridge, MA 02139-4307

phone: (617) 253-2721 fax: (617) 258-8850 email: osm@mit.edu

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LONG-TERM GOALS

The long-term goals of this research are: (i) to identify all relevant physical processes that participate in and contribute significantly to sediment transport in near-shore coastal waters; (ii) to investigate each of the identified processes in order to understand the underlying physics in a quantitative manner; (iii) to develop simple predictive models for each process; and (iv) to incorporate the simple predictive process-models in a predictive model for beach profile response to the action of waves and currents.

OBJECTIVES

The present research is concerned with the effect of fluid accelerations, which is synonymous to pressure-gradients, on fluid-sediment interaction in near-shore waters, i.e. under near-breaking or broken waves. In particular, the objective is to ascertain the importance of the subsurface sediment transport rate induced purely by the strong pressure gradient (acceleration) associated with the passage overhead of the steep forward-leaning front of a near-breaking or broken wave relative to the surficial sheet flow sediment transport rate induced by shear stresses and pressure gradients.

APPROACH

We have adopted a two-pronged (experimental and theoretical) approach to the examination of the potential contribution of pressure-induced subsurface transport to the net sediment transport rate under breaking waves.

Experiments are performed in a laboratory wave flume in which waves are generated by a programmable wave maker, climb a ramp and enter an elevated horizontal shelf (false bottom) where wave breaking is triggered. The breaking wave propagates over the test section consisting of a 10 cm-wide, 1 m-long and 15 cm-deep clear Lucite tray, containing lightweight plastic beads, installed in the false bottom along the centerline of the flume.

The Lucite tray protruding below the false bottom is directly observable through the glass sidewalls of the wave flume, and the subsurface movement of the plastic beads may be recorded photographically by inserting a ~2cm-long column of colored beads that spans the entire width of the Lucite tray.

Velocity measurements are obtained with an ADV-system which is mounted on rails and also serves to obtain bottom profiles along the length of the tray. From the velocity measurements an approximation

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for the pressure distribution along the bottom is obtained by use of non-linear wave theory. From the bottom profile measurements, combined with the conservation of sediment equation, estimates of total sediment transport rates (surficial plus subsurface) are obtained.

A theoretical model for pressure-induced subsurface motion of non-cohesive sediments is developed. The model is based on the static determination of a limiting slip-circle for which the driving moment associated with the pressure distribution on the sediment-fluid interface is balanced by the stabilizing moment of inter-granular shear stresses at failure along the limiting slip-circle. The material above this limiting slip-circle is in a state of plastic failure and a kinematically admissible solution consists of concentric circle-segments rotating around their common center. The unsteady moment of momentum equation for any of these segments in failure may be solved and leads to a prediction of the angular rotation of any circular segment above the limiting slip-circle as a function of the time-varying driving moment associated with the pressure distribution passing overhead. The model's output estimates the pressure-induced horizontal forward displacement of subsurface particles, as a function of depth, during passage of the steep front of a breaking wave.

Personnel carrying out the research are, in addition to the PI, Mr. William "Mack" Durham, a Graduate Student Research Assistant on the project, who will be receiving his Masters Degree based on a thesis derived from the research; and Ms. Elisabeth Lundgren, an undergraduate student supported as a UROP student, who assisted in conducting experiments and analyzing data over the summer, 2006.

WORK COMPLETED

The test section, briefly described above, has been installed in the large 76-cm wide, 90-cm deep and 20-m long wave flume in the Ralph M. Parsons Laboratory's Gunther Environmental Fluid Mechanics Laboratory.

The "sediment" used in the experiments is Polyethylene Terephthalate (PET) whose relevant physical characteristics have been determined to be: diameter = $d = 1.1 \pm 0.1$ mm, density = $\rho_b = 1.27 \pm 0.01$ g/cm³, porosity = $n = 0.37 \pm 0.02$, and angle of internal friction $\varphi = 34^\circ.8 \pm 1^\circ$ and $39^\circ.2 \pm 1^\circ.1$ for loosely and densely packed deposits, respectively.

Experiments have been performed with this "sediment" subjected to the passage of both a sequence of solitary waves and wave bursts consisting of groups of three waves. Subsurface displacements have been recorded photographically with a Canon PowerShot S230 digital camera used for both stills and for video, with a frame rate of 15 frames per second. From the videos, shot during passage of a breaking wave overhead, frame by frame analysis determines when the column of colored beads start to move, when it reaches maximum forward deflection, and where it eventually comes to rest after the wave has passed. Since we are recording the displacement of the column of colored beads along the sidewalls of the Lucite tray, we cut a slice along the centerline of the Lucite tray, by inserting a thin Lucite sheet into the bed, to see if the observed displacements were representative of the displacements over the entire width of the column of colored beads. In this manner, we have verified the validity of our experimental procedure for the determination of subsurface, pressure-gradient-induced movements of a sediment bed (see Figure 2 presented in the Results Section).

The time-series of horizontal velocity, $u(t)$, obtained from the ADV at a sampling rate of 25 Hz, were smoothed and used to obtain estimates of the corresponding pressure gradient from

$$-\frac{\partial p}{\partial x} = \rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} \right) \approx \rho \frac{\partial u}{\partial t} \left(1 - \frac{u}{c} \right) \quad (1)$$

in which the non-linear term is approximated by assuming the wave to be approximately progressive and of permanent form, i.e., replacing $\partial/\partial t$ by $-c \partial/\partial x$, with c = the phase velocity of the wave. This assumption is also used to switch back and forth between spatial and temporal pressure variations. Averaging an ensemble of 10 wave realizations produced a very consistent record of the bottom pressure distribution, $p(x)$, associated with our breaking waves.

The ADV was mounted on a carriage which could be moved along the length of the Lucite tray, and the ADV output of distance above bottom is used as a bottom-profiling system. The accuracy of this procedure was documented by placing a known volume of "sediment" in the tray and then profiling this deposit to obtain agreement (within 2%) between measured and known volume. From measurements of the bottom elevation changes along the tray, $\Delta z_b(x)$, the sediment continuity equation can be used to obtain an estimate of the total (surficial plus subsurface) sediment transport rate, q_T , associated with the passage of a broken wave:

$$q_T(x) = q_{T0} - (1-n) \int_0^x \Delta z_b(x) dx \quad (2)$$

where q_{T0} = total transport rate at the up-wave ($x = 0$) end of the tray, which was obtained from an up-wave sediment collection bag. The predicted sediment transport rate at the down-wave end of the tray agrees within 1% with the amount captured by a collection bag. This verifies conclusively our methodology for the determination of total transport rates.

A simple, approximate, theoretical model for the prediction of the subsurface motion of sediment induced by the pressure gradient associated with the breaking wave passing overhead has been developed. The model is, as mentioned earlier, based on the concept of a soil-mechanics-type of failure of the porous bed caused by the seepage forces exerted on the soil skeleton by the subsurface porewater flow induced by the pressure gradient. The model's concept is a series of concentric slip-circles along which the sediment (soil) is assumed to fail. For the limiting slip-circle, i.e. the one reaching deepest into the sediment bed, the driving moment associated with the pressure distribution is just balanced by the maximum stabilizing moment that can be mobilized at failure along the limiting slip circle by the intergranular shear stress in the cohesionless soil. All the sediment above the limiting slip-circle is in a state of failure, i.e. having a pressure-induced moment, M_d , exceeding the maximum realizable stabilizing moment, M_s , from intergranular shear stresses along the circular failure plane of radius r . From the moment of momentum equation we obtain the approximate dynamic equation

$$I_r d^2 \theta_r / dt^2 + Mg_r \theta_r = Md_r(t) - Ms_r \quad (3)$$

in which the first term represents the moment of inertia around C , the second term the restoring moment from gravity around C , and the right hand side is the net driving moment which produces the angular rotation, $\theta_r(t)$, of the circle-segment of radius r .

Evaluating the driving moment $Md_r(t)$ by translating the bottom pressure distribution associated with the breaking wave passing across the slip-circle's intersection with the horizontal bed surface, a simple differential equation is obtained from which $\theta_r(t)$ can be obtained for a slip-circle of radius r subject to the initial condition of $\theta_r = d\theta_r/dt = 0$ at $t = 0$. The movement along a particular slip-circle terminates when $d\theta_r/dt = 0$ and the corresponding displacement, $r\theta_{max}$, can be obtained. In this manner the subsurface displacement profile can be estimated.

RESULTS

Figure 1 shows a comparison of the experimentally obtained subsurface forward displacements associated with the passage of the steep forward-leaning front of a solitary wave and the predicted displacements obtained from our simple theoretical model using the lightweight (PET) "sediment" characteristics and the bottom pressure distribution inferred from our velocity measurements.

Given the simplicity of our theoretical model, its ability to reproduce the essence of the measured displacements is quite remarkable. Thus, measured forward displacements associated with the passage of the first solitary wave over a newly "deposited" (loose) bed agrees favorably with our model predictions for an internal angle of friction $\varphi = 34^\circ$ to 36° . Recalling that our independent determination of φ was $34^\circ.8 \pm 1^\circ$ the agreement for the first wave is very encouraging. The experimentally observed decrease in displacement (both in magnitude and depth below sediment-fluid interface) with number of solitary waves is also captured by our simple theoretical model by increasing the value of φ , which corresponds to a strengthening of the sediment due to the reworking caused by preceding waves similar to our independent finding of an increase in φ to $39^\circ.2 \pm 1^\circ.1$ for densely packed samples of PET beads.

However, before accepting the utility of the simple theoretical model it should be emphasized that its success, as illustrated in Figure 1, is for the forward displacements observed during passage of the steep forward-leaning front of a breaking solitary wave. Whereas the theoretical model predicts that there should be no subsurface displacements after passage of the steep wave front, i.e. the predicted displacements shown in Figure 1 should be identical to the net displacement caused during passage of a solitary wave, the experiments tell a different story.

After reaching its maximum forward displacement, shown in Figure 1, the column of colored beads rebounds and comes to rest at a location closer to its initial position prior to the arrival of the breaking solitary wave, i.e. resulting in a net displacement caused by the passage of a solitary wave that is considerably less (by a factor of ~ 5) than that suggested by its forward displacement under the steep front of the breaking wave. A clue to why this rebound takes place may be found in Figure 2(b) which shows the column of colored beads after the passage of several (~ 50) solitary waves. Clearly the column, while displaced, is still intact, i.e. individual beads have not been sliding across each other but stayed in contact with their neighbors throughout the experiment. Thus, in the soil mechanics sense, a failure of the subsurface sediments really has not taken place during passage of breaking waves overhead. Instead, the strong pressure gradient under the steep front of the wave has forced the column to deflect in the forward direction but not sufficiently to cause an actual failure. After passage of the wave front the column is left in an unstable state and rebounds in an elastic manner once the force that caused its original deflection is removed. The integrity of the column of colored beads, as it appears along the sidewall of the Lucite tray in Figure 2(b), is somewhat broken up in the middle of the Lucite tray (Figure 2(c)). The dislocation of individual beads in the center of the tray may, however,

have been caused by the insertion of the Lucite sheets into the bed during preparation of the center cut shown in Figure 2(c).

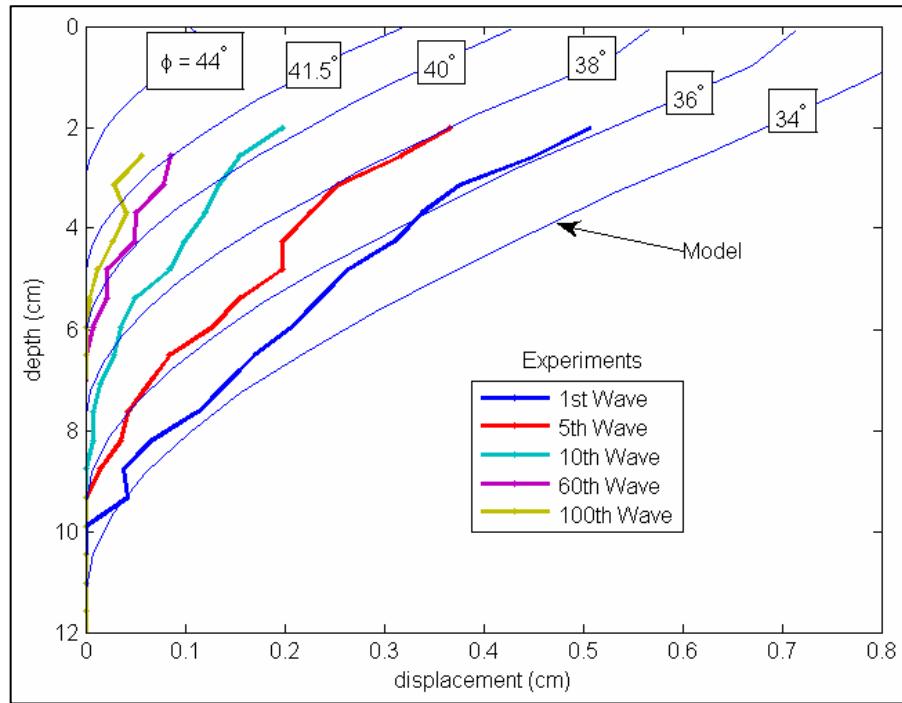


Figure 1: Predicted and measured subsurface forward displacements during passage of breaking solitary waves [graph: displacements of 0.5 and 0.1 cm at bed-surface decreasing to zero at 10 and 6 cm depth for first and fiftieth wave, respectively]

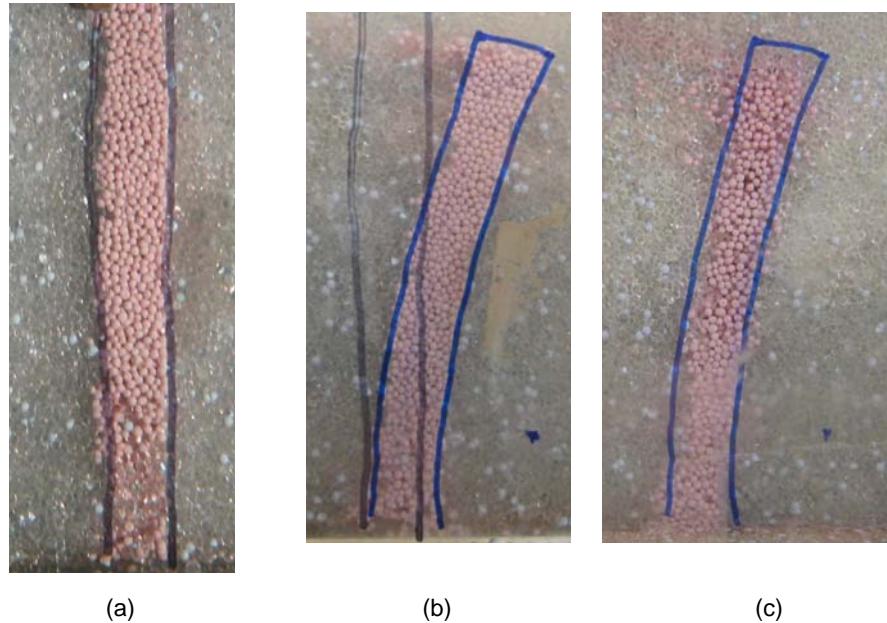


Figure 2: Observed net displacements of column of colored beads: (a) initial position; (b) position along sidewall after \sim 50 solitary waves; (c) same as (b) but along center line of tray [graph: column's net displacement increases from zero at \sim 10cm depth to several cm at the top]

The measurements of the total sediment transport rate using Eq. (2) gives $q_T \sim 3 \text{ cm}^3/\text{cm}$ per solitary wave passing overhead. For comparison, the subsurface sediment transport rate inferred from just the *forward* displacement during passage of the steep front of the breaking solitary wave (Figure 1), amounts to $\sim 1.3 \text{ cm}^3/\text{cm}$ for the first and $\sim 0.1 \text{ cm}^3/\text{cm}$ for the 100th wave. Given the fact that the net subsurface transport rate, i.e. accounting for the "rebound", is lower than the values obtained from Figure 1, by a factor of ~ 5 , it would appear that the subsurface transport rate is at most $\sim 10\%$ of the total. However, this estimate of the relative importance of surficial and subsurface transport rates is obtained for a solitary wave, for which all surficial transport is in the direction of wave propagation. For a periodic wave the forward velocity (and surficial transport) is followed by a backward velocity (and surficial transport), i.e. a net transport that is a potentially small difference between the forward and backward transport. In contrast, the subsurface transport is exclusively associated with the passage of the steep front of the breaking wave and this should not be significantly different for periodic and solitary waves. We can therefore not, without further experiments involving periodic waves and including the effect of bottom slope by tilting our test section, make a final conclusion regarding the potential significance of the contribution of the subsurface sediment transport mechanisms to the total net cross-shore sediment transport rate in near-shore coastal waters.

IMPACT/APPLICATION

The present research will provide a physically-based parameterization of the potential contribution of the pressure-gradient-induced subsurface transport mechanism to net cross-shore sediment transport in near-shore coastal waters. If the subsurface transport mechanism is found to be important, it *must* be included in models of beach profile response to wave action. If it is found to be unimportant, it may *safely* be neglected. Either way, the community of beach profile modelers will benefit from the results of this research.